The Gunnar Mine: An Episyenite-hosted, Granite-related Uranium Deposit in the Beaverlodge Uranium District

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Abstract

The past-producing Gunnar mine exploited one of a number of vein-type uranium deposits within the prolific Beaverlodge uranium camp near Uranium City in northwestern Saskatchewan. Between 1955 and 1963, the mine produced 6,892 tons of uranium at an average grade of 0.148% U. Three weeks of re-mapping at 1:10 000 scale this summer showed the area to be underlain by Archean orthogneiss and the intrusive 2321 ±3 Ma Gunnar granite, both of which are intruded by mafic dykes that are thought to be co-genetic with Murmac Bay Group basalts. Minor aplitic granite and transposed biotite pegmatite dykes were probably emplaced during 1.94 to 1.90 Ga amphibolite-facies metamorphism, prior to late intrusion of northeast-striking muscovite pegmatite dykes.

Uranium mineralization at the Gunnar mine occurred within altered rocks of the Gunnar granite, in close proximity to the contact with the orthogneiss, and near the junction of three faults. Alteration of the granite occurred in irregular pipe-like bodies up to hundreds of metres in size and included the replacement of primary K-feldspar by albite, and the dissolution of quartz to produce 'episyenite'. Hematization was both intense and widespread; and carbonate, locally emplaced in the matrix and as veins, has been variably dissolved leaving a vuggy 'sponge rock'. The moderately south-southeast–plunging orebody formed in brecciated episyenite and comprised pitchblende and minor uranophane as veins, colloform coatings, and disseminated grains. Associated gangue minerals include quartz, chlorite, kaolinite, and trace specular hematite, ilmenite, chalcopyrite, pyrite, and galena. Spectrometer readings show that the uranium content of episyenite distal to mineralization is not appreciably diminished, supporting the inference of former workers that it is not the source of the uranium, but functions rather as a highly porous conduit for uranium-bearing fluids.

Episyenite derived from Gunnar granite was also noted about 800 m east of the pit and on the eastern shore of Spring Lake; both localities contain elevated eU (equivalent uranium) values at isolated sites proximal to regional lineaments. At other localities in the Gunnar area, uranium occurs along, and at the intersection of, fractures. These uranium localities can be hosted by any of the major rock types, but are disproportionately more common in the gabbro.

Keywords: *Gunnar mine, Beaverlodge uranium district, Beaverlodge Domain, uranium, vein-type uranium deposit, episyenite, Gunnar granite, Crackingstone Peninsula, Saskatchewan.*

1. Introduction

The Gunnar mine (Figure 1) exploited one of a number of vein-type uranium deposits within the prolific Beaverlodge uranium district near Uranium City in northwestern Saskatchewan (Figure 2). Between 1955 and 1963, the mine produced 6,892 tons of uranium at an average grade of 0.148% U, second in tonnage only to the Ace-Fay-Verna mine (Figure 2). Although much has been written about the Gunnar deposit (Robinson, 1955; Canadian Institute of Mining and Metallurgy, 1957; Jolliffe and Evoy, 1957; Evoy, 1961, 1986; Lang *et al.*, 1962; Beck, 1969), most is based on old descriptions that predate modern uranium deposit models and classification schemes (*e.g.*, Nash *et al.*, 1981; Ruzicka, 1993; Cuney and Kyser, 2008a; International Atomic Energy Agency, 2009). Since the Gunnar mine site is also scheduled for reclamation in the near future, a re-visit was considered timely. This paper describes the results of a three-week field study aimed at re-mapping and describing the deposit in the light of recent developments in the genesis of uranium deposits.

The southwestern Crackingstone Peninsula has been mapped in detail at 1:9,600 scale (Bell, 1962a, 1962b) and as part of a more regional 1:20 000-scale mapping project (Ashton *et al.*, 2000). In order to put the deposit study into a regional context, the area around the mine site was re-mapped at 1:10 000 scale (simplified version in Figure 3; see accompanying map separate). A more detailed map was completed at property scale to take advantage of some large cleaned outcrops immediately north of the open pit and south of Mudford Lake, and to demonstrate some of the area's lithological and structural complexities (Figure 3). A hand-held, high-sensitivity, gamma and neutron

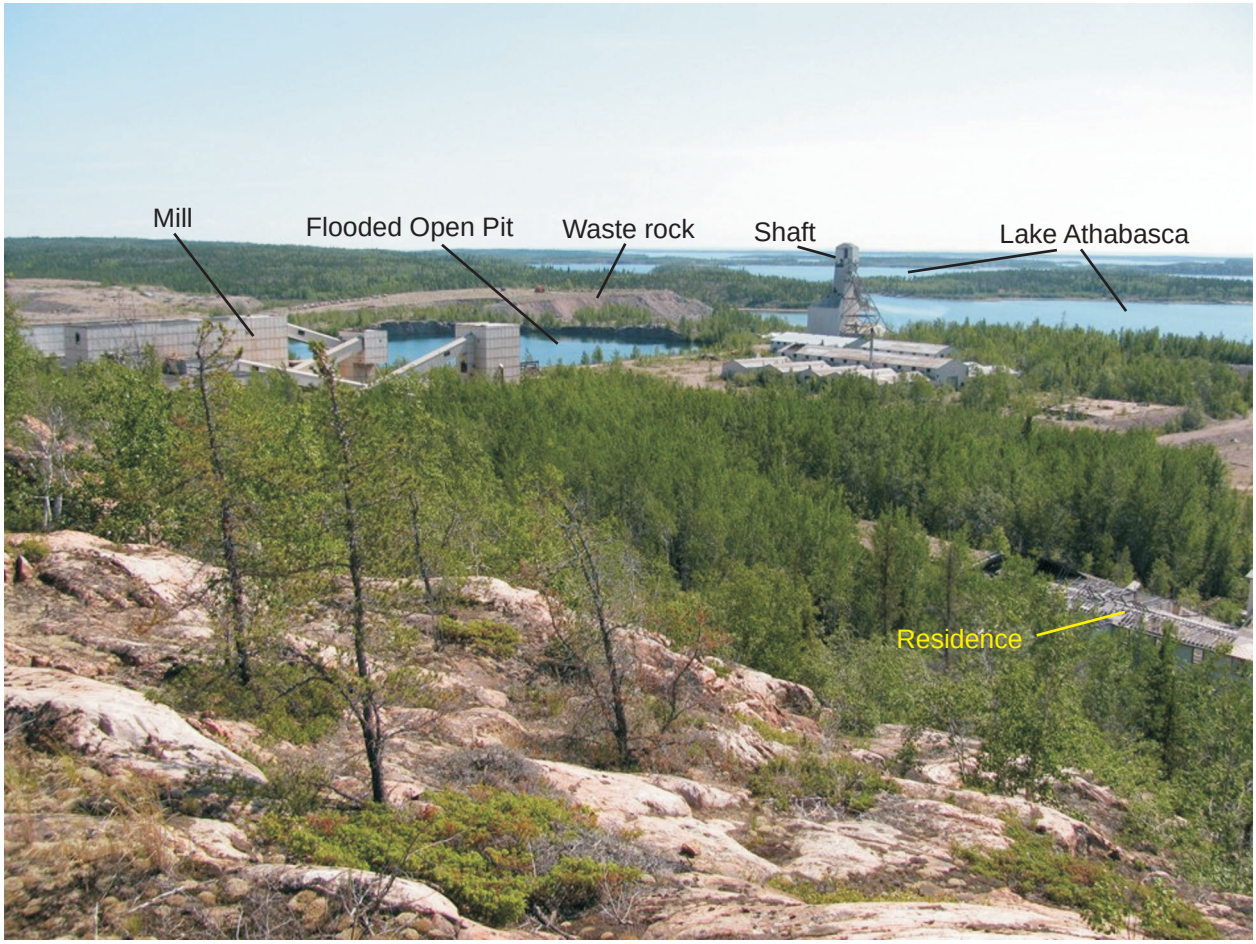


Figure 1 - The Gunnar mine site as of summer, 2010, viewed towards the southeast; rock in the foreground is the orthogneiss.

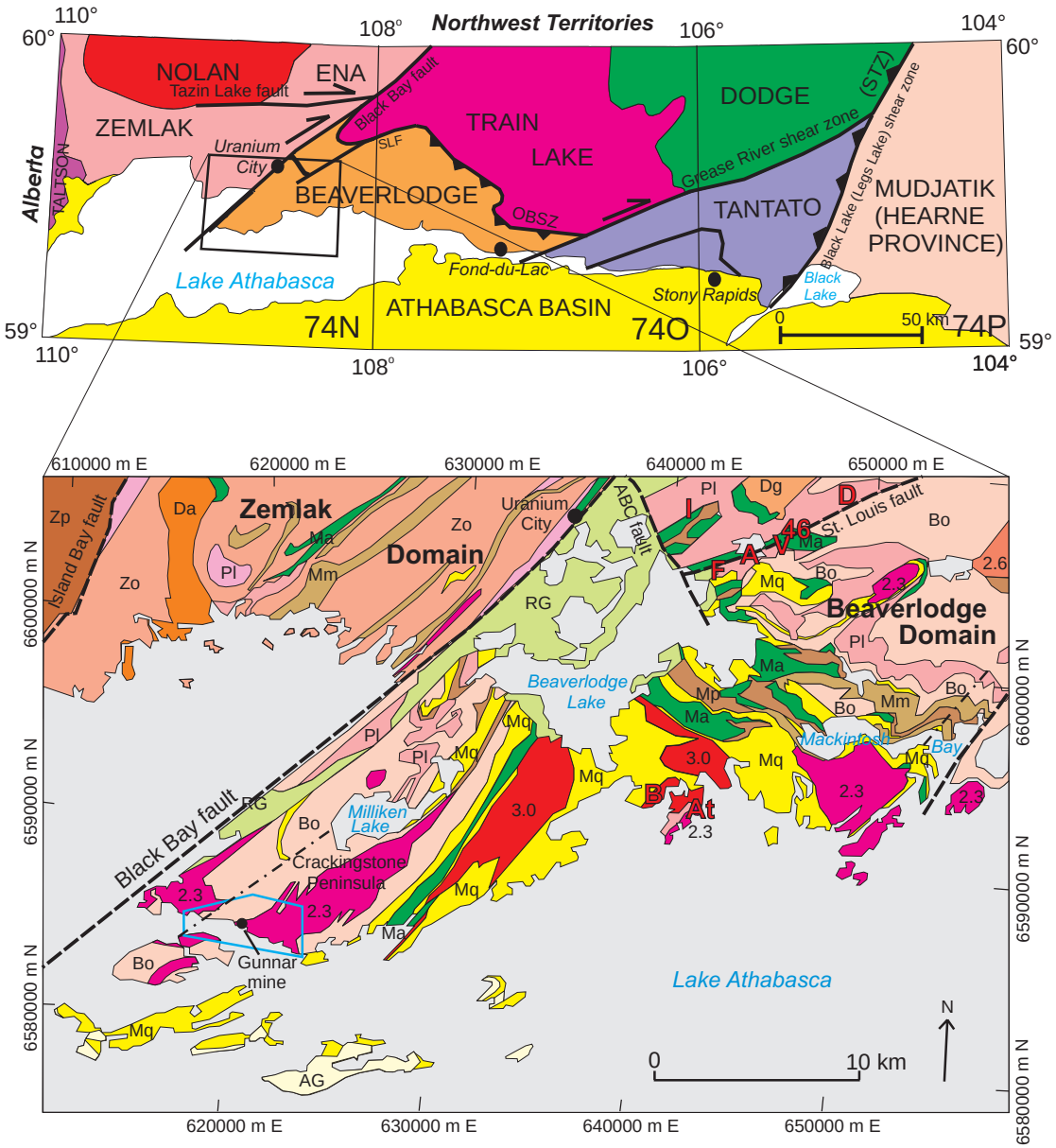
radiation spectrometer (Radiation Solutions RS-230) was used to establish high, low, and average concentrations of eK, eU, and eTh for the major rock types (Table 1) and to study their variability in altered rocks and in the vicinity of uranium showings. These spectrometer assays are reported, but should not be used as substitutes for direct rock assays.

Access and Exposure

The Gunnar mine is accessible by float plane from Stony Rapids (Figure 2), although a private airstrip located 3 km north of the mine site is connected by a gravel road, so access by wheeled aircraft is also possible with permission. It can also be reached by boat from Bushell, located on the northern shore of Lake Athabasca 10 km south of Uranium City. Elevation ranges from about 250 m at Lake Athabasca to 325 m on inland hilltops. The bedrock exposure is generally good, although waste rock excavated from the open pit covers many of the original outcrops in the immediate vicinity of the mine, and the pit was flooded at the time of mine closure.

2. Regional Geology

The Gunnar mine area lies within the southwestern Beaverlodge Domain. The regional geology has been previously described (Ashton *et al.*, 2000; Ashton and Hartlaub, 2008), so this paper mainly deals with the immediate mine area, which is dominated by orthogneisses of probable Archean origin and the 2321 ±3 Ma (Hartlaub *et al.*, 2007) Gunnar granite. Although the orthogneisses contain leucosome derived from injection and probably *in situ* partial melting, the Gunnar granite lacks evidence of anatexis, suggesting that granite emplacement post-dated a major thermotectonic event. *Circa* 2.37 Ga metamorphic zircon recovered from Archean orthogneiss 15 km north of the Gunnar mine and west of the Black Bay fault (Ashton *et al.*, 2009a) suggests that this event was the *ca.* 2.35 Ga Arrowsmith Orogeny (Berman *et al.*, 2005; Hartlaub *et al.*, 2007). Mafic dykes that intrude both the orthogneiss and Gunnar granite are thought to be part of a suite of gabbros emplaced into both the lowermost Murmac Bay Group, thought to be deposited between 2.33 and <2.17 Ga (Ashton *et al.*, 2009a), and its *ca.* 3.0 Ga granitoid basement



Paleoproterozoic Rocks

- AG Athabasca Group (<1.75 Ga)
- RG Martin Group (*ca.* 1.8 Ga)
- Pl Pink leucogranite (*ca.* 1.9 Ga)
- Dg Donaldson Lake Granite (*ca.* 1.9 Ga)

Murmac Bay Group (2.3 to <2.2 Ga)

- Mm Mixed supracrustal rocks
- Mp Pelitic gneiss
- Ma Amphibolite
- Mq Quartzite
- 2.3 2.3 Ga granite

Rocks of Unknown Age

- Da Aluminous diatexite
- Zp Zemlak pelitic gneiss
- Zo Zemlak orthogneiss

Archean Rocks

- 2.6 2.6 Ga granite
- Bo Beaverlodge orthogneiss (2.9 Ga in part)
- 3.0 3.0 Ga granite

Figure 2 - Location of the Gunnar mine relative to regional geology. Blue box outlines area covered in Figure 3. Abbreviations: A, F, V – Ace-Fay-Verna mine; At – Athona gold deposit; B – Box gold mine; D – Dubyna Lake uranium deposit; I – 'Intermediate Zone'; 46 – '46 Zone'; and dash-dot lines are F3 fold traces. OBSZ, Oldman-Bulyea shear zone; STZ, Snowbird Tectonic Zone; and SLF, St. Louis fault. Note that all UTM grid coordinates in this paper are in NAD83, Zone 12.

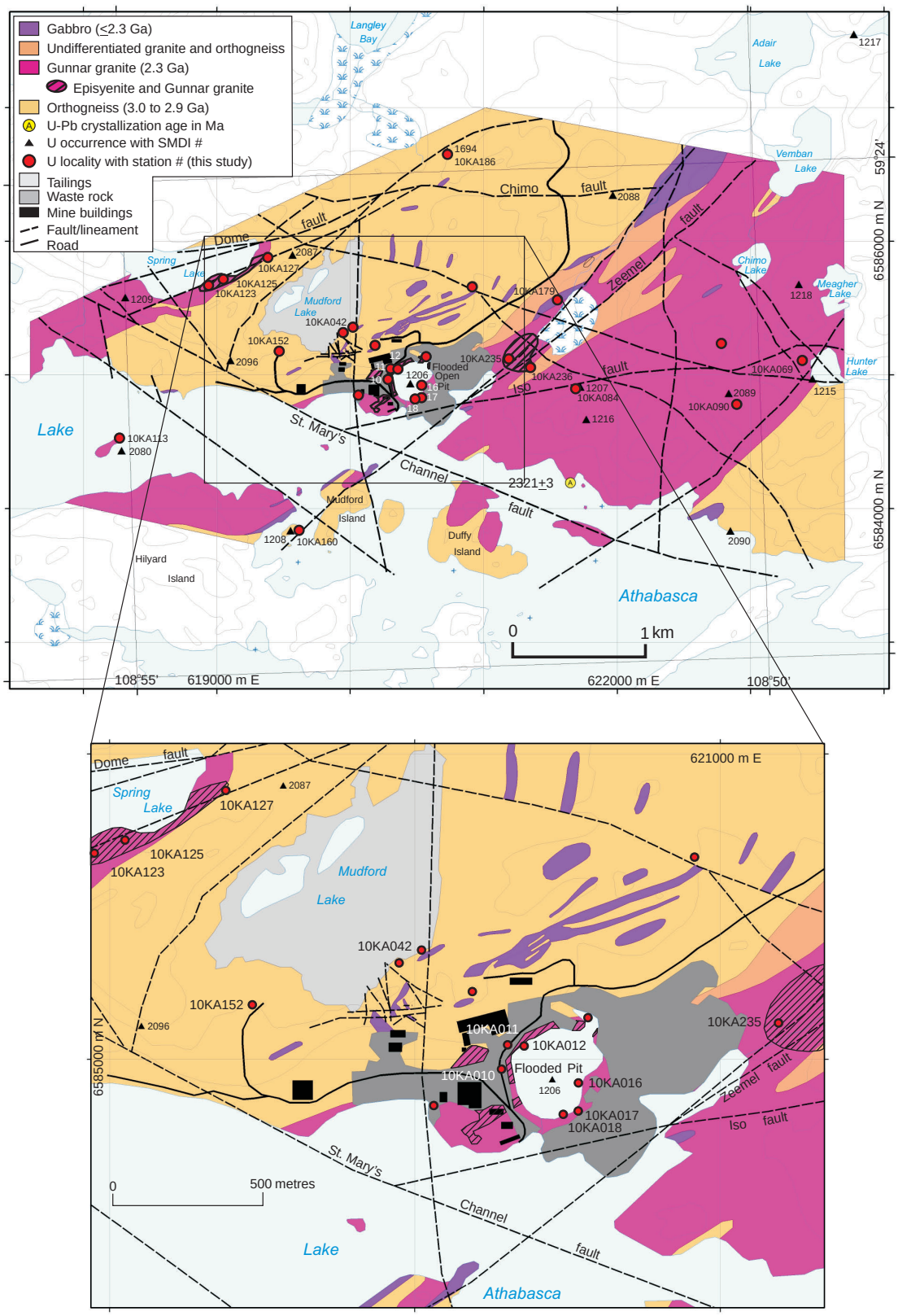


Figure 3 - Simplified geological map of the Gunnar mine area with a close-up of the mine workings. Labelled uranium localities contain >50 ppm eU based on spectrometer assays.

Table 1 - Average spectrometer and magnetic susceptibility values for non-mineralized samples of common rock types.

	Spectrometer									Magnetic Susceptibility (x 10^{-3})		
Rock Type	n	K (%)	1σ	U (ppm)	1σ	Th (ppm)	1σ	Th/U	1σ	n	Average	1σ
Late muscovite pegmatite	4	5.0	0.9	3.5	1.3	5.1	2.3	1.6	0.6	3	0.06	0.04
Gabbro	47	1.8	0.9	3.8	3.2	4.3	2.8	2.0	1.9	46	5.93	14.29
Episyenite	12	0.7	0.3	9.2	3.6	40.8	13.2	5.3	2.6	4	2.26	4.19
Gunnar granite	95	3.8	1.5	7.0	3.3	34.5	10.2	5.8	3.2	86	0.43	1.52
Orthogneiss	101	2.3	1.4	5.3	4.0	17.7	12.0	4.6	3.8	97	2.59	5.03

* n denotes number of samples analyzed; 1σ represents error based on one standard deviation

(Persons, 1983; Hartlaub *et al.*, 2004) on the eastern Crackingstone Peninsula (Figure 2). The strong geochemical similarities between the mafic dykes and Murmac Bay Group basalts suggest that they are co-magmatic (Hartlaub *et al.*, 2004). Subsequent aplitic granites and biotite granitic pegmatite dykes probably accompanied two amphibolite-facies metamorphic events at 1.94 to 1.92 Ga and 1.91 to 1.90 Ga (Ashton *et al.*, 2009b). Post-deformational, northeast-striking, straight-walled muscovite pegmatite dykes are common in the southeastern part of the Gunnar mine area. They are thought to post-date uranium mineralization and have yielded a K-Ar muscovite age of 1815 ±90 Ma (Lowdon, 1961, p39), which should be a reasonable estimate of the crystallization age given their post-metamorphic character.

A recent regional synthesis (Ashton *et al.*, 2009b) lists D1-D2 as producing the earliest, recognizable, east-southeast–striking foliation and isoclinal folding of it (*ca.* 1.94 to 1.92 Ga); D3 as producing a regional northeast-striking overprint defined by close to isoclinal folds and faults (*ca.* 1.91 to 1.90 Ga); and D4 as a higher crustal level phase responsible for open, north-trending folds and extensive brittle-ductile faulting (*ca.* 1.8 Ga).

3. Unit Descriptions

The oldest rocks in the immediate Gunnar mine area (Figure 3) are orthogneisses (unit Gag) generally comprising several interlayered rock types at outcrop scale. The dominant component is variably strained granite to granodiorite containing 5 to 10% chloritized biotite. The best-preserved examples are pink to grey, medium-grained, and homogeneous (Figure 4), but with increasing strain, the colour of this dominant phase changes to grey or white, the grain size decreases, and the rock takes on a stronger foliation (Figure 5). Decametre-scale layers of grey finer grained gneiss may represent shear zones derived from the same granitic precursor. Many outcrops also include medium- to coarse-grained granitic sheets that were probably derived during metamorphism by partial melting, either *in situ* or nearby and injected (Figure 5). The end result is a multi-phase rock that is further complicated by localized shearing and intense fracturing accompanied by hematitic alteration (Figure 6) that has led most previous workers to interpret these rocks as paragneisses (Jolliffe and Evoy, 1957; Bell, 1962a; Lang *et al.*, 1962; Beck, 1969; Evoy, 1986). The southeast-dipping contact between the orthogneiss and the Gunnar granite in the vicinity of the mine represents one such zone of high deformation. Though somewhat patchy and difficult to outline, the orthogneiss is particularly sheared and overprinted by brittle fracturing over an area up to 400 m wide and



Figure 4 - Well preserved basement granite from orthogneiss unit on northern shore of Lake Athabasca 2.5 km east of the Gunnar mine (UTM 622794 m E, 6583841 m N).



Figure 5 - Orthogneiss comprising fine- to medium-grained grey paleosome derived from basement granitoid and isoclinally folded medium-grained pink leucosome. Strong fabric in the leucosome was induced by late shearing; from the same outcrop as Figure 4 on the northern shore of Lake Athabasca, 2.5 km east of the Gunnar mine (UTM 622794 m E, 6583841 m N).



Figure 6 - Intensely fractured and hematized orthogneiss from 850 m northwest of the flooded Gunnar open pit (UTM 619606 m E, 6585251 m N). Central mafic layer is a transposed gabbro dyke.

2 km along strike to the northeast of the open pit. Gabbroic sheets up to tens of metres thick are common within the orthogneiss there, and are responsible for abundant epidote alteration. Magnetite content is highly variable in the orthogneisses, but most have low to moderate magnetic susceptibilities (average 2.59 x 10^{-3} SI; Table 1). A range of granitoid compositions is reflected in the 0.3 to 6.2% eK [1] spectrometer values (average 2.3% eK) for non-mineralized samples of the orthogneiss unit. An average value of 5.3 ppm eU is above the 2.7 ppm average for upper continental crust (Kyser and Cuney, 2008) and, together with average values of 17.7 ppm eTh, and a 4.6 Th/U ratio, is consistent with an igneous origin (Cuney and Kyser, 2008a). A sample of orthogneiss collected about 4 km west of the current map area, yielded a 2941 ±8 Ma age (Ashton *et al.*, 2009a), consistent with derivation from the *ca*. 3.0 Ga granitoid suite (Persons, 1983; Hartlaub *et al.*, 2004) exposed on the eastern Crackingstone Peninsula and Beaverlodge Lake area (Figure 2).

The orthogneiss is intruded by the Gunnar granite (unit Grg), a homogeneous, pink, coarse-grained rock (Figure 7) containing 2 to 7% variably chloritized biotite, 20 to 30% quartz, 30 to 35% plagioclase, 35 to 40% microcline, and trace amounts of zircon, apatite, and opaque minerals. Muscovite, carbonate, and hematite are minor but common alteration products, and also occur in thin veinlets at microscopic scale. Although the Gunnar granite appears to post-date the early metamorphic event responsible for partially melting the orthogneisses, it has been subjected to amphibolite-facies conditions and is variably foliated to lineated. The primary coarse feldspars, up to 1 cm in length, are locally deformed into augen and variably recrystallized to medium-grained aggregates. Aplite dykes and pods up to several metres thick are locally emplaced within the main coarse-grained phase of the granite and are probably co-genetic. The Gunnar granite has low magnetic susceptibility (average 0.43 x 10^{-3} SI; Table 1) and contains an average of 3.8% eK, somewhat higher than that of the orthogneiss unit (average 2.3 % eK), reflecting its more granitic composition. Average spectrometer values of 7.0 ppm eU and 34.5 ppm eTh are also somewhat higher than those of the orthogneiss, making the Gunnar granite a more fertile potential source for uranium. The average Th/U ratio of 5.8 is consistent with an igneous origin (Cuney and Kyser, 2008a). A sample of the main coarse-grained phase from within the study area 1 km east of the flooded Gunnar open pit (Figure 3) yielded a 2321 ±3 Ma zircon crystallization age (Hartlaub *et al.*, 2007).



Figure 7 - Well-preserved Gunnar granite from the northern shore of Lake Athabasca 1 km east of the Gunnar mine (UTM 620905 m E, 6584342 m N), and in close proximity to the geochronology location. Note the 1 cm grain size of feldspar and abundance of white interstitial quartz.

Within the Gunnar granite, typically adjacent to contacts with the orthogneiss and faults, are zones of 'episyenite', an alteration product of the granite produced by metasomatic removal of quartz and replacement of microcline by albite. The result is a pale-pink to red, medium-grained rock that is easily

[1] Note that K contents were measured and reported as %K and not $\%K_2O$. To convert, multiply %K value by 1.2047.

distinguished from the precursor granite by the absence of coarse quartz (Figure 8). The total or partial removal of 20 to 30% quartz, together with the replacement of microcline by albite may have resulted in: a) a loss of rock volume due to compaction (Figure 8), leaving a rock containing 90 to 95% albite with minor chlorite and carbonate; b) a rock containing abundant voids (Figure 9), which may have facilitated the local development of collapse breccias; or c) a rock in which such voids have been subsequently filled by carbonate, which has locally undergone surface weathering to produce a pitted texture (Figure 10). Vein and disseminated carbonate is ubiquitous in the episyenites, comprising up to 30% of the rock volume where it has completely filled the voids left by quartz dissolution. Chlorite is also found in all samples, comprising 2 to 5% (locally up to 15%) of the rock as a replacement along with titanium-bearing minerals of primary biotite, and as radiating aggregates attributed to late precipitation from fluids. Minor opaque minerals are common, including hematite, which also occurs as fine inclusions in the 60 to 90% plagioclase. Early plagioclase grains contain the most hematite inclusions, whereas younger grains of albite precipitated from the alteration fluids tend to be subhedral, relatively clear of inclusions, and spatially related to the carbonate. Spectrometer measurements illustrate the extent of potassium depletion, which ranges from an average of 3.8% eK in the Gunnar granite to 0.7% eK in the episyenite (Table 1). Although the episyenite hosts many of the uranium occurrences, including the Gunnar deposit, the 9.2 ppm eU and 40.8 ppm eTh average concentrations do not show any appreciable depletion relative to the precursor Gunnar granite (Table 1), supporting the previous inference that these episyenite alteration rocks are not the source of the uranium.

Due to the lithological similarities of rocks in the orthogneiss and Gunnar granite units, their distinction along shared contacts can be difficult. There are few problems in areas of low strain and good exposure such as the islands in St. Mary's Channel, but in the Zeemel fault area (Figure 3), the strain is high, prompting a unit of undifferentiated orthogneiss and Gunnar granite (unit Gu). It is likely that both units are represented, but their sheared nature renders the coarse-grained components almost indistinguishable, and both units also contain fine- to medium-grained granitic components. The two units could be intimately juxtaposed in this zone due to the intrusion of Gunnar granite dykes and sheets into the older orthogneiss and/or by structural repetition.

Black, fine- to medium-grained gabbro (unit Gb) has been emplaced into the orthogneiss unit and Gunnar granite as sheets ranging from centimetres to tens of metres thick (Figure 3). Most contain roughly equal portions of hornblende and plagioclase, although in many localities the hornblende is variably replaced by biotite. Fluids associated with late muscovite pegmatite dykes that are spatially related to some of these occurrences may be responsible for the potassium-metasomatism, although potassic fluids would also have been released by the replacement of K-feldspar by



Figure 8 - Typical 'episyenite' derived from Gunnar granite by removal of quartz and replacement of microcline by albite; from the eastern shore of Spring Lake (UTM 618988 m E, 6585674 m N). Note reddish colour produced by addition of hematite and the absence of coarse quartz relative to the typical Gunnar granite in Figure 7.



Figure 9 - Pitted episyenite derived by removal of quartz in a zone of fluid alteration; from island 2 km southwest of the Gunnar mine (UTM 618113 m E, 6584454 m N).

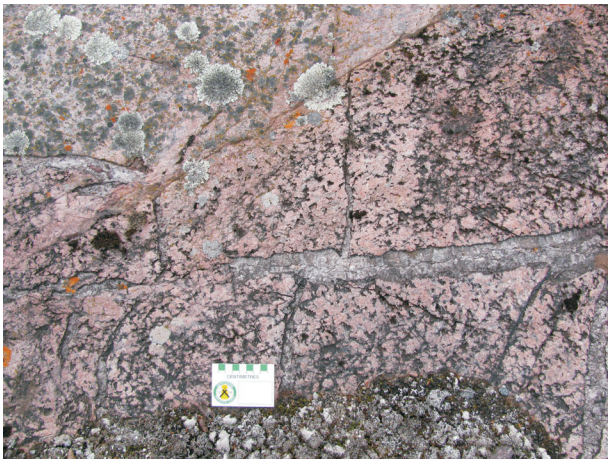


Figure 10 - Carbonatized episyenite containing a carbonate vein from the northwestern edge of Gunnar open pit (UTM 620462 m E, 6585114 m N). Pitted portion of the surface illustrates removal of secondary carbonate throughout the rock by surface weathering.

albite in the episyenites. The gabbroic rocks locally weather white and black and take on a more dioritic appearance, containing about 35% hornblende. All of the gabbroic rocks have undergone the same degree of metamorphism and deformation as the Gunnar granite and are generally concordant to the regional foliation. Two exceptions are mafic hornblende-plagioclase dykes located 350 m northwest of the Gunnar open pit, which crosscut the regional foliation at a small angle. These may be younger than the other gabbro bodies or less transposed by subsequent deformation. The gabbros are variably magnetic and, on average, are the most magnetic rocks in the area (average 5.93 x 10^{-3} SI; Table 1). They have low average concentrations of eU (3.8 ppm) and eTh (4.3 ppm) as expected from their basic composition. The 1.8% eK average may be artificially high due to supplemental potassium radiation from the granitoid rocks hosting these dominantly metre-scale sheets. The gabbro unit is considered correlative with a suite of gabbro sills and dykes that intruded the *ca.* 3.0 Ga basement to the Murmac Bay Group on the eastern Crackingstone Peninsula (Ashton and Hartlaub, 2008) They are geochemically near-identical to the Murmac Bay group basalts, and therefore are thought to be co-genetic (Hartlaub *et al.*, 2004). Assuming this scenario, they were likely emplaced at or shortly after 2.3 Ga (Ashton and Hunter, 2003; Ashton *et al.*, 2009a).

Pink and white biotite granite dykes and sheets, ranging from medium grained to pegmatitic, may be several metres thick. They typically contain 0 to 5% biotite, range from massive to gneissic, and are locally sheared. They were likely emplaced during the main regional metamorphic events between 1.94 and 1.90 Ga.

Late muscovite pegmatite dykes (unit Gpm) intrude the Gunnar granite and, to a lesser extent the orthogneiss, in a northeast-striking zone extending from Hilyard and Mudford islands in the southwest to the Meagher Lake area (see accompanying map separate). They are white to pink, massive, and 2 to 15 m thick. Typical dykes are zoned, with coarse-grained quartz-feldspar margins containing about 10 to 15% randomly oriented, centimetre-scale muscovite books, and medium-grained to pegmatitic cores dominated by granophyric intergrowths and quartz. Pegmatitic feldspars are locally aligned perpendicular to the dyke walls, and tourmaline was noted at one occurrence at the northeastern end of Mudford Island. The muscovite pegmatites are non-magnetic and have average values of 5.0% eK, 3.5 ppm eU, and 5.1 ppm eTh (Table 1). A dyke near the Gunnar mine has yielded an 1815 ±90 Ma K-Ar age obtained from muscovite which, in spite of the large error, is thought to be a reasonable estimate of the crystallization age (Lowdon, 1961).

4. Structure

Owing to the granitoid nature of most rocks in the area, the early structural history is not well preserved. A 2.37 Ga metamorphic event recorded in orthogneiss west of the Black Bay fault (Figure 2; Ashton *et al.*, 2009a) may mark the early pre-Gunnar granite deformation that affected the orthogneiss. Otherwise, it is known from nearby supracrustal rocks that the area underwent two phases of regional deformation, the first probably at 1.94 to 1.92 Ga that resulted in a broadly east-west structural fabric (Ashton *et al.*, 2009b). The main S1-S2 composite regional foliation affecting the orthogneiss, Gunnar granite, and gabbro is thought to have formed at this time. This was followed by a later phase of 1.91 to 1.90 Ga metamorphism and deformation (D3) that was responsible for tight to isoclinal, regional folds that produced a northeast-trending structural straight belt in the area hosting the Gunnar mine. This was the phase responsible for the regional fold broadly defined by the Gunnar granite (Figure 2). Rare minor folds and a northeast-striking biotite foliation that crosscuts the main S1 fabric may be manifestations of this deformation.

A gently to moderately south-plunging regional lineation is defined both by localized tectonic stretching (Figure 11) and mineral elongation (mainly hornblende and quartz). It occurs regionally, but is best developed within localized zones of high shear strain ranging from a few centimetres to several metres wide. Many of the latter are down-dip lineations suggesting that they are the result of dip-slip displacement (Figure 11). Some of the regional lineations may have formed during early thrusting along the originally south-dipping S1-S2 foliation, but many of those associated with layer-parallel southeast-dipping shear zones probably result from north- to northwest-verging D3 thrusting. Those spatially related to crosscutting, commonly east-west shear zones, may reflect late D4 normal faulting as seen elsewhere in the region (Ashton *et al.*, 2009b).

The early, dominantly ductile D1-D3 deformation was followed by uplift and subsequent upper crustal-level D4 deformation characterized by broad open folds with north-striking axial planes (*e.g.*, that defined by the Martin Group to the north; Ashton *et al.*, 2009b) and brittle-ductile to brittle shearing and faulting. Rare cross-cutting north-striking foliations are probably manifestations of this deformational phase in the Gunnar region. It has been previously suggested that a broadly east-west stress regime, possibly resulting from a combination of Trans-Hudson orogenesis to the southeast and tectonic accretion to the far west was responsible for this D4 deformation (Ashton *et al.*, 2009b). The resultant shearing/faulting directions included a conjugate set of dextral northeast- and sinistral northwest-striking strike-slip faults, and broadly east-west extensional faults. The regional network of late brittle to brittle-ductile faults in the Gunnar mine area (Figure 3) appears broadly consistent with this interpretation (Figures 2 and 3), although convincing kinematic indicators of fault displacement were generally not recognized. Examples include the Zeemel and Iso faults, representing the dextral and extensional fault directions, respectively. The

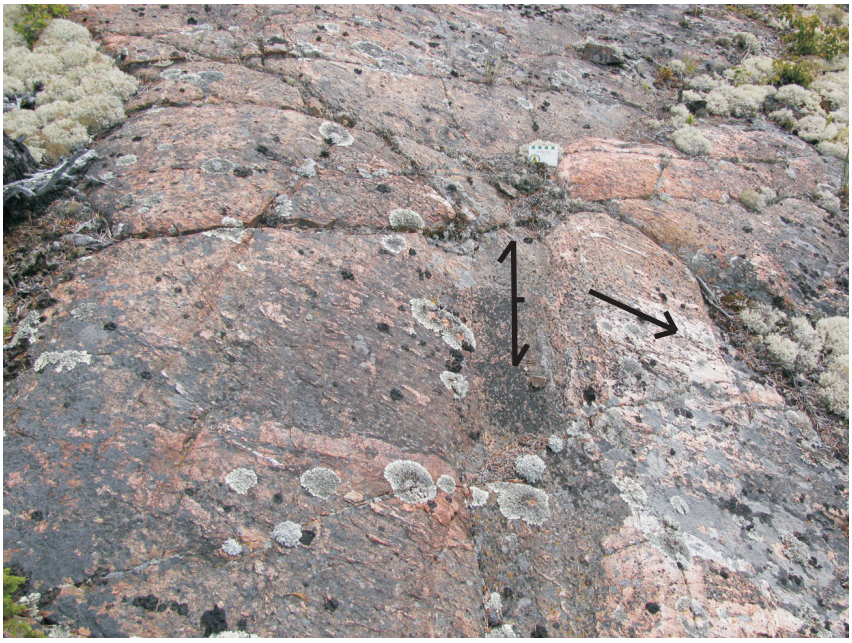


Figure 11 - Gently south-southeast–dipping shear zone (foliation symbol on recessive weathering layer) exhibiting down-dip stretching lineation (arrow) developed in highly fractured orthogneiss from 125 m west of Gunnar pit (UTM 619252 m E, 6584957 m N).

sinistral strike-slip faults are not as well developed regionally as their dextral counterparts, and the Gunnar area is no exception. They may be represented by northwesterly striking segments of the more east-west–oriented extensional faults (Figures 2 and 3). Relatively uncommon north-striking faults may represent reverse faults in this stress regime.

Outcrop-scale ductile shear zones occur in a variety of orientations (Figure 12a) and, as mentioned above, probably include zones developed during D2-D4. Nevertheless, most are northeast/southwest striking and the majority of those exhibiting kinematic indicators are dextral. A weaker set of southeast-striking shear zones is thought to include the sinistral component of a conjugate set, whereas the east-west orientations are considered extensional and the north-south zones contractional, broadly consistent with the east-west–shortening model for D4.

Outcrop-scale brittle faults also occur in a diverse range of orientations dominated by northeast and southeast strikes (Figure 12b); however, those showing apparent offsets do not conform to the model as well as the brittle-ductile shear zones. Five of the six apparent dextral faults strike southeastward or northward, whereas four of the six sinistral apparent offsets strike either northward or southwestward. This discrepancy may be attributable to oblique or dominantly dip slip on some or all of these faults so that the apparent displacements are misleading, or it may be due to multiple generations of fault development.

Open fractures are dominantly southeast/northwest and northeast/southwest striking (Figure 12c), similar to, but distinct from, the pattern shown by the brittle faults. Quartz veins are common, particularly in intense zones of brittle and brittle-ductile strain. Vein orientations are diverse, mimicking the orientation of the ductile shear zones more closely than those of the faults and fractures (Figure 12d). One of the two main directions is broadly east-west, an orientation not common for either faults or fractures, possibly indicating that this marks the plane of extension. The second most common direction is northeast striking, followed by southeast striking, perhaps suggesting that the dextral and sinistral conjugate shear/fault set is used for fluid transport and eventual precipitation.

St. Mary's Channel fault is considered an east-west structure and probable normal fault. It is exposed over several tens of metres in Gunnar granite on northeastern Duffy Island and the island to the east (Figure 3) as zones of sheared granite, clay alteration, intense quartz veining, intense hematization (and possible de-quartzification), and brecciation (Figure 13). Other noteworthy faults include the Zeemel, Iso, and Dome structures. The Zeemel fault appears to be a network of closely spaced, similarly oriented structures (Figure 3). It has historically been placed through the Gunnar mine site immediately south of the open pit and extended northeastward to Vembam Lake (Bell, 1962a, 1962b), but another branch of the network extends farther west following Zeemel Creek to Adair Lake. In addition to the episyenite alteration at the Gunnar mine site, other zones were recognized where these branches of the Zeemel fault are intersected by an unnamed northwest-striking fault about 1 km east of the pit (Figure 3). The other extensive zone of episyenite is located along the eastern side of Spring Lake, about 200 m south of the northeast-striking Dome fault (Bell, 1962a), and along a parallel lineament that may represent another fault. Most uranium localities are also situated very close to faults/lineaments, further suggesting that the faults have acted as major conduits for fluids and therefore represent a major control on mineralization.

Rocks at the Gunnar mine site appear more highly strained than elsewhere. Brittle-ductile faults disrupt the continuity of gabbroic marker units and are accompanied by intense epidotization in and near the mafic rocks (Figure 14), along with quartz veining and hackly fracturing (Figure 6) in all rock types in a zone extending up to

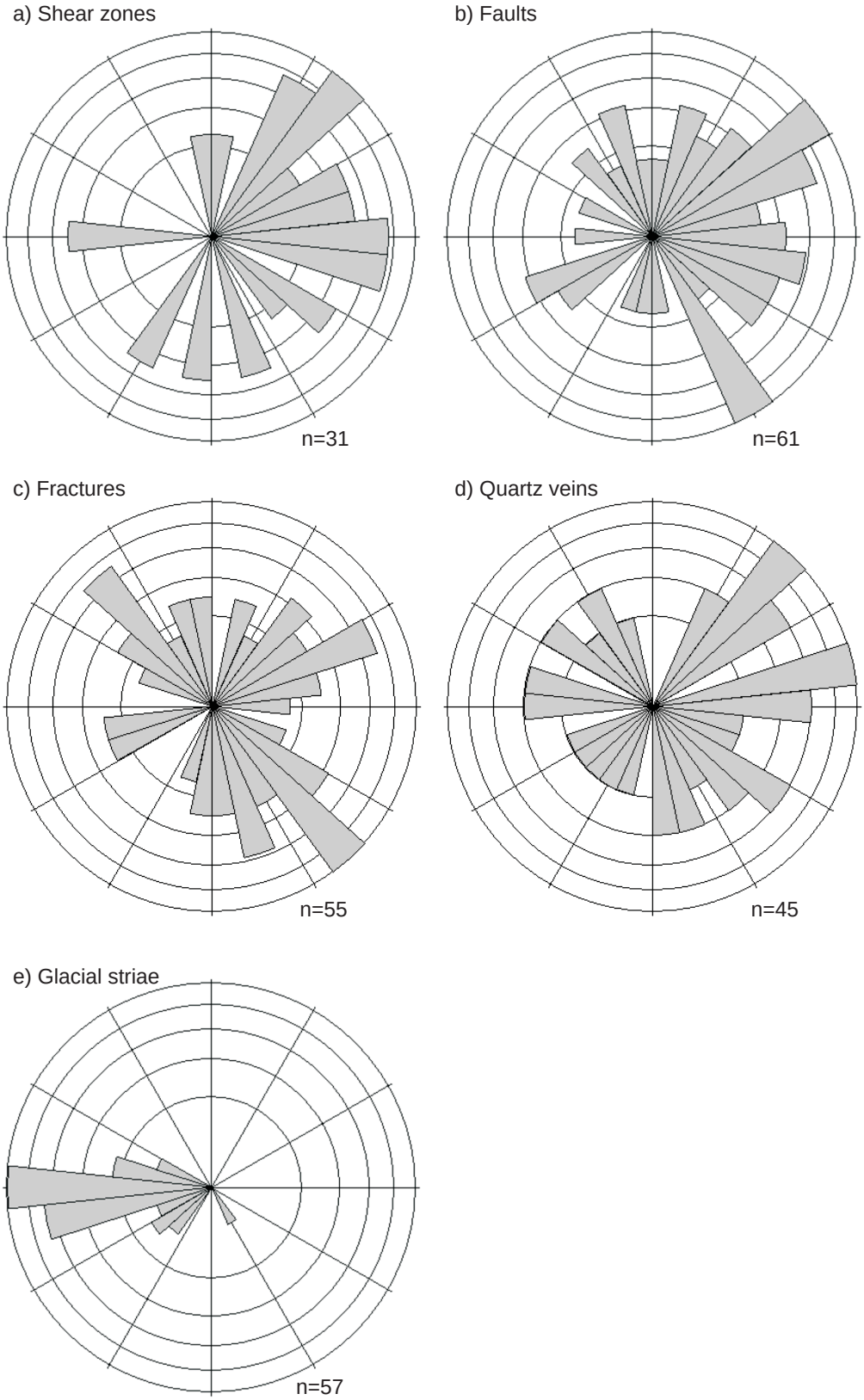


Figure 12 - Rose diagrams showing total measured: a) shear directions, b) fault directions, c) fractures, d) quartz veins, and e) glacial striae. Class size is 12° for each; n represents the number of measurements.

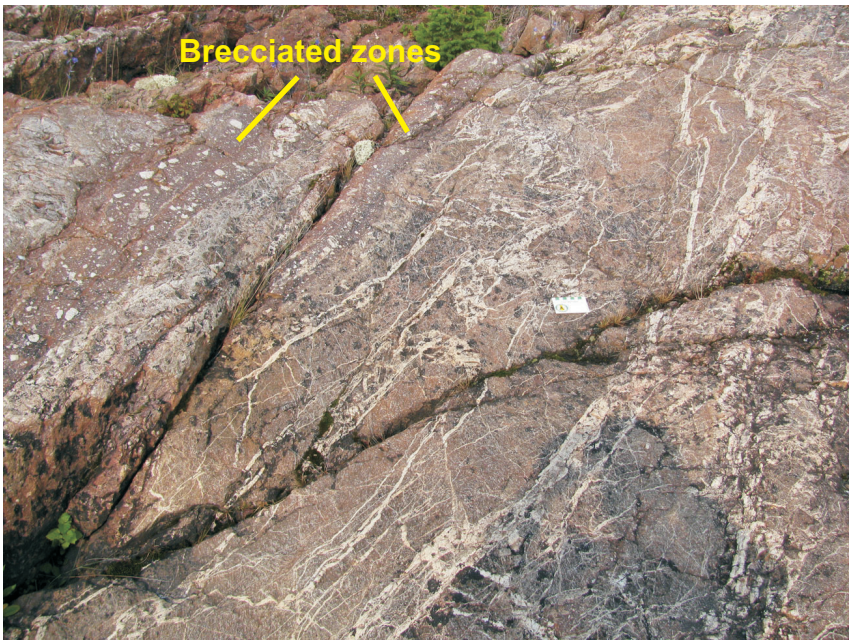


Figure 13 - Exposure of St. Mary's Channel fault developed in altered Gunnar granite at the eastern end of Duffy Island (UTM 621851 m E, 6583829 m N). Note quartz vein stockwork and intensely hematized zones containing brecciated fragments of vein quartz.

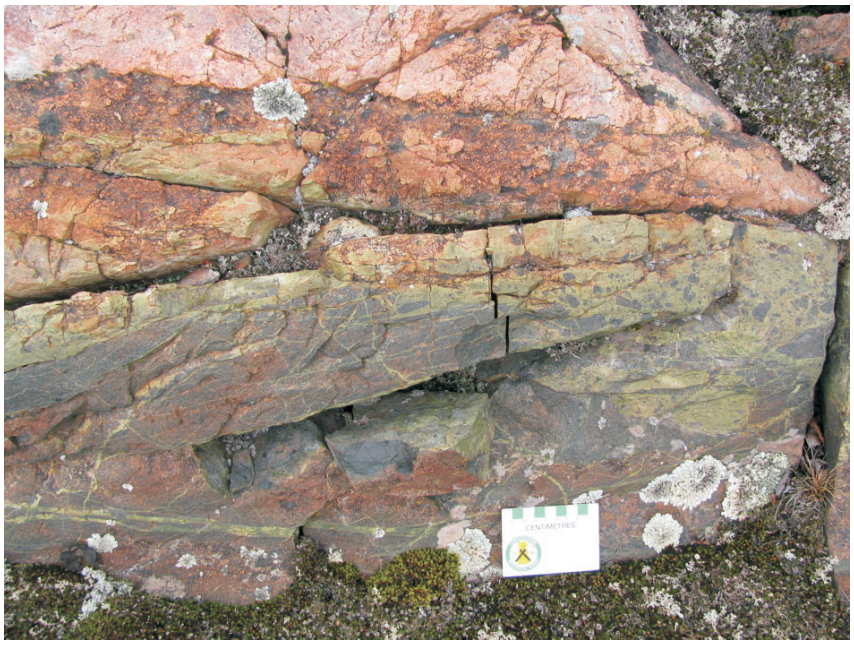


Figure 14 - Highly fractured and faulted orthogneiss and gabbro from 200 m west of the Gunnar pit (UTM 620061 m E, 6585018 m N). Note extensive epidote alteration within and adjacent to gabbro in lower part of photo.

400 m northwest of the Gunnar granite/orthogneiss contact. The Gunnar granite side of the contact is not so well exposed, but there are indications of heterogeneous intense strain as well as the episyenitic alteration. This high-strain zone may result from brittle displacement along the orthogneiss/Gunnar granite contact due to competency contrast.

5. Quaternary Geology

Quaternary drift cover is discontinuous and generally thin; however, erosional features, including roches moutonées and glacial striae, are commonly preserved, particularly on the bedrock exposures defining the shores of Lake Athabasca (see accompanying map separate). At several localities, protected surfaces facilitated the recognition of two generations of striae and led to the determination of at least part of the ice-flow history. Three distinct generations of ice flow are recorded by the striae (Figure 12e; accompanying map separate). North of Lake Athabasca, and on protected surfaces along its shores, southwest-oriented striae (222° to 242°) are preserved. The main (and younger) ice-flow direction, however, is westward (251° to 292°), broadly parallel to the northern shore of Lake Athabasca. South-southeast–oriented striae (155°) recorded at a single outcrop are older than the west-oriented generation and may represent the oldest indications of ice-flow direction. Dominantly southwestward ice flow (198° to 245°) superseded by westward ice flow (250° to 280°), and preceded by a poorly defined southeasterly flow (120° to 166°) was also documented in a previous and more detailed study 70 km to the east (Campbell *et al.*, 2006). Ice-flow indicators, recording early westerly (250° to 280°) and southerly (170° to 200°) flows in that study area to the east, were not recorded in the Gunnar mine area.

6. Economic Geology

Although the focus of this study was the Gunnar mine, there are 13 other uranium occurrences listed in the Saskatchewan Mineral Deposit Index (SMDI) within the area mapped (Figure 3), some of which were visited. In

addition, other exposures of rocks containing >20 ppm U (a randomly chosen criterion well above background) were identified with the aid of the spectrometer (Figure 3; see accompanying map separate). They have been distinguished from the SMDI occurrences, and termed uranium 'localities' since they are based on spectrometer rather than geochemical assays. Although many of the uranium localities found during this study coincide with SMDI occurrences, others do not. This may be due to: 1) the more representative nature of some SMDI occurrences (*i.e.*, locations being a non-mineralized point central to a number of nearby occurrences); 2) their imprecise locations with errors potentially enhanced by conversions from latitudes and longitudes to UTM coordinates and/or UTM zone and datum conversions (*e.g.*, the plotting of SMDI #2080 about 200 m south of its actual location on a small island north of Hilyard Island in Lake Athabasca; Figure 3, accompanying map separate); or 3) the overgrown nature of some SMDI occurrences making them difficult to find. Study of these uranium localities was greatly aided by having the spectrometer, which was used not only to distinguish eU radiation from that of eTh and eK, but also to determine the spatial relationships of radioactivity and alteration (*i.e.*, K depletion) at mineralized sites. Locations, settings, and spectrometer assays for mineral localities containing more than 50 ppm eU are listed in Table 2. One drawback encountered when using the spectrometer was its inability to accurately distinguish eK from eU radiation in areas of anomalously high eU concentrations. It inconsistently yielded artificially high %eK values where eU concentrations were above 400 ppm, and affected all readings above 2500 ppm U. The problem was likely due to an improper internal correction (J. Mwenifumbo, pers. comm., 2008). It prevented meaningful potassium concentrations from being measured within about 1 m of anomalous uranium concentrations.

The Gunnar granite and episyenite proved to be the most 'fertile' potential source rocks at 7.0 and 9.2 ppm eU, respectively (Table 1), well above the average upper continental crustal concentration of 2.7 ppm (Kyser and Cuney, 2008) and similar to the 4 to 6 ppm typical of I- and S-type granites (Whalen *et al.*, 1987), and 5 to 6 ppm of late- to post-orogenic granites (Rogers and Greenburg, 1990).

The mineralization has been divided into three types based on the nature of the host rocks. It includes mineralization in: a) altered Gunnar granite (*i.e.*, episyenite); b) gabbro hosted mainly by Gunnar granite; and c) orthogneiss.

a) Uranium in Altered Gunnar Granite (Episyenite)

Episyenites are generally derived from granites that have undergone metasomatic replacement of quartz and K-feldspar by albite (Cathelineau, 1986; Petersson and Eliasson, 1997; International Atomic Energy Agency, 2009). The mobility of other elements varies,

Table 2 - Uranium localities in the Gunnar mine area based on spectrometer assays during this study.

Station #	Location	Easting	Northing	Description	SMDI #	Total cps [1]	ppm eU	ppm eTh	% eK [2]
10KA010	Gunnar pit	620297	6585005	episyenite on pit edge	1206	3,000	835.2	0	90
10KA011	Gunnar pit	620303	6585011	episyenite on pit edge	1206	2,700	216	209	29
10KA012	Gunnar pit	620347	6585055	Gunnar granite on pit edge	1206	4,000	299.6	46.3	1.3
10KA016	Gunnar pit	620549	6584894	Gunnar granite on pit edge	1206	5,000	346.3	42.1	4.5
10KA017	Gunnar pit	620536	6584830	Gunnar granite on pit edge	1206	10,000	458.4	33.3	2.8
10KA018	Gunnar pit	620508	6584799	Gunnar granite on pit edge	1206	1,500	54.5	36	4
10KA042	southeast edge of tailings	620033	6585329	gabbro at edge of tailings; due to tailings?		6,200	317	38	2.6
10KA069	3 km east of pit	623373	6585145	fracture in Gunnar granite at gabbro contact	1215	2,800	122.2	43.9	7.5
10KA084	1.5 km east of Gunnar pit	621727	6584910	fracture intersection in 10 m thick sheared gabbro	1207	4,000	315.4	10.8	1.1
10KA090	2.5 km east of Gunnar pit	622899	6584766	fractures in 10 m thick gabbro	2089	25,000	2381	62.1	0.6
10KA123	Spring Lake	618988	6585674	episyenite	1209, 2087	40,000	3940	302	36.7
10KA125	Spring Lake	619050	6585718	episyenite	1209, 2087	16,500	1455	72.7	3
10KA127	Spring Lake	619382	6585881	episyenite slice in orthogneiss	1209, 2087	14,000	959.6	36.1	3.7
10KA152	1 km west of Gunnar pit	619425	6585160	fracture in orthogneiss		2,100	93.5	25.7	0.9
10KA160	southwest of Mudford Island	619637	6583828	fracture in orthogneiss	1208	5,000	459.2	2.2	90
10KA179	1.2 km northeast of Gunnar pit	621555	6585564	fracture in ≥25 m thick gabbro		5,000	294.0	15.2	3.4
10KA186	1.7 km north of Gunnar pit	620730	6586653	fractures at gabbro/leucogranite contacts	1694	15,000	1260	35	0
10KA235	1 km northeast of Gunnar pit	621193	6585119	faulted gabbro/Gunnar granite contact		54,000	6293	598.7	90
10KA236	1 km northeast of Gunnar pit	621353	6585057	faulted gabbro at Gunnar granite/orthogneiss contact		65,500	10000	2941	90

Notes: [1] cps - counts per second and [2] % eK >7.5 are spurious due to improper internal correction.

but the dominant process involves sodium metasomatism. Episyenites are found in a variety of geographic and temporal settings (*e.g.*, International Atomic Energy Agency, 2009) and may host uranium (Cuney and Kyser, 2008b), gold-molybdenum (*e.g.*, in the Abitibi Greenstone Belt of Québec, Jébrac and Harnois, 1991), or tin (*e.g.*, in the Amazonian craton; Costi *et al.*, 2002) mineralization, or may be barren of any anomalous metal concentrations (Petersson and Eliasson, 1997). Thus, they are not restricted to hosting granite-related uranium deposits.



Figure 15 - Zone of episyenite alteration within Gunnar granite on the northern edge of the Gunnar pit (UTM 620538 m E, 6585083 m N). Note irregular nature of episyenite contact (dotted line).

Uranium mineralization occurring within episyenite in the study area includes the Gunnar mine (SMDI #1206) and the Spring Lake localities (SMDI #1209). A weakly mineralized uranium locality on the westernmost island in St. Mary's Channel (SMDI #2080; Figure 3) has also been included in this group since it exhibits de-quartzification, although its potassium concentration does not show the depletion generally accompanying albitization. Episyenite, which was described above, was also noted along Zeemel Creek adjacent to the Zeemel fault system (Figure 3). It occurs in zones up to hundred of metres in size and has sharp irregular contacts with unaltered Gunnar granite (Figures 9 and 15), consistent with a fluid-controlled origin.

1) Owing to the inability to go underground or into the flooded open pit, direct observation of the Gunnar deposit was limited (Figure 1). Thus, much of the following description comes from Evoy (1986). The deposit was hosted by a pipe-like episyenite zone within the Gunnar granite, in close proximity to the contact with the orthogneiss, and near the junction of three faults (Iso, Zeemel, and St. Mary's Channel). The alteration history began with the albitization of K-feldspar, followed by the dissolution of quartz, after which time the resulting albitite was fractured and brecciated prior to the introduction of carbonate (Evoy, 1986). Hematization was both intense and widespread; and the carbonate, locally emplaced in the matrix and as veins, was variably dissolved leaving a vuggy 'sponge rock'. Albitization and mineralization tended to follow the northeast-striking, foliation-parallel fractures, and to a lesser degree, north-striking fractures. In the third dimension (Figure 16), the orebody mimicked the moderately southeast-plunging, pipe-like shape of the episyenite. This may be partly attributed to the pre-existing south-plunging lineation, which is present in the episyenites and would have helped to focus fluid flow. Deformation that was accommodated along layering planes in the orthogneiss was thought to have caused fracturing in the episyenite (Evoy, 1986), although evidence for intense fracturing of the orthogneiss was also noted during the current study. In spite of the occurrence of patchy episyenite along regional faults, fractures and zones of brecciation were considered more important controls on mineralization (Evoy, 1986).

   Thin sections of episyenite from the current study contain 2 to 5% chlorite both as a replacement of biotite, and a younger hydrothermal generation comprising rosettes of radiating fibres that Evoy (1986) reported as having penninite composition. The episyenite also contains up to 30% carbonate as vein and matrix material, up to 8% unidentified opaque minerals, 45 to 90% albite, and traces of white mica, leucoxene, hematite, and unidentified accessory minerals. Traces of quartz and K-feldspar occur as late cavity fill and veinlets. Carbonate veins cut albite–opaque mineral±hematite veinlets, consistent with their late emplacement, although some of these are in turn cut by chlorite veinlets, suggesting a temporal overlap and/or multiple generations of chlorite emplacement.

   The orebody formed in brecciated episyenite and took up about 15% of the total volume of altered rock. Pitchblende was the principle ore mineral, occurring as mainly disseminated grains, but also as small veinlets and patches up to 5 cm wide, coatings on fractures and breccia fragments, and interstitially within the breccia (Evoy, 1986). Minor uranophane coated fractures and filled open cavities. Gangue minerals included introduced quartz, chlorite, and kaolinite, along with trace specular hematite, ilmenite, chalcopyrite, pyrite and galena (Evoy, 1986). Introduction of the ore was thought to post-date albitization and at least part of the de-quartzification (Evoy, 1961). The interpreted mineral paragenetic sequence was: 1) chlorite and iron sulphides; 2) quartz, orthoclase, ore, and titanium-bearing minerals; and 3) carbonate.

2) The large zone of Gunnar granite in the Spring Lake area (Figure 3) hosts several uranium occurrences (SMDI #1209 and #2087). Most of these are poorly exposed, but along the eastern side of the lake, the mineralization is situated within extensive but patchy orangey-pink to red episyenite, and is locally well exposed (10KA123 on Figure 3; Table 2). The episyenite retains remnants of the original coarse grain size and northeast-striking S1 foliation of the precursor Gunnar granite, with which it exhibits a sharp but irregular contact attributed to a

fluid front. It contains 5 to 10% chlorite including generations derived from biotite and hydrothermal alteration, 15% carbonate, and about 75% broken and variably recrystallized albite grains containing abundant hematite inclusions. Leucoxene is associated with the chlorite, and unidentified opaque and accessory minerals are also present in trace amounts. Several spectrometer assays illustrate the potassium depletion in most of the episyenite, although this is shown to some extent even in Gunnar granite that has not undergone de-quartzification (Figure 17). At another trenched uranium locality 50 m to the east, the host Gunnar granite has undergone de-quartzification but retained its primary K-feldspar, containing 5% chlorite, including some of the radiating hydrothermal variety, 10% carbonate, 50% K-feldspar, 35% plagioclase, trace leucoxene, and minor ≤1 mm voids.

3) On a small island in western St. Mary's Channel (Figure 3; 10KA113; SMDI #2080), the Gunnar granite exhibits northwest-striking zones displaying a pitted weathering surface due to quartz dissolution (Figure 9). The altered rock differs from typical episyenite by lacking the characteristic potassium depletion, yielding spectrometer assays of: 7.4 ppm eU, 45.0 ppm eTh, and 3.1% eK. Anomalous uranium concentrations are located along a steep, similarly oriented fault 5 m away containing 33.7 ppm eU, 96.0 ppm eTh, and 4.4% eK. A discontinuous, 1 cm-thick, biotite schist along the fault may represent a sheared and altered gabbro sheet. A moderately southeast-dipping fracture set displaying gently south-plunging slickensides (*i.e.*, dip slip) intersects the fault in the vicinity of the anomalous uranium concentration.

b) Uranium in Gabbroic Rocks

At the majority of uranium localities, the mineralization is hosted by gabbroic sheets or occurs at faulted/fractured contacts between the gabbro and either the Gunnar granite or, less commonly, orthogneiss. Some of these uranium localities are within areas of episyenitic alteration of the Gunnar granite whereas at others alteration of the adjacent granite was not recognized.

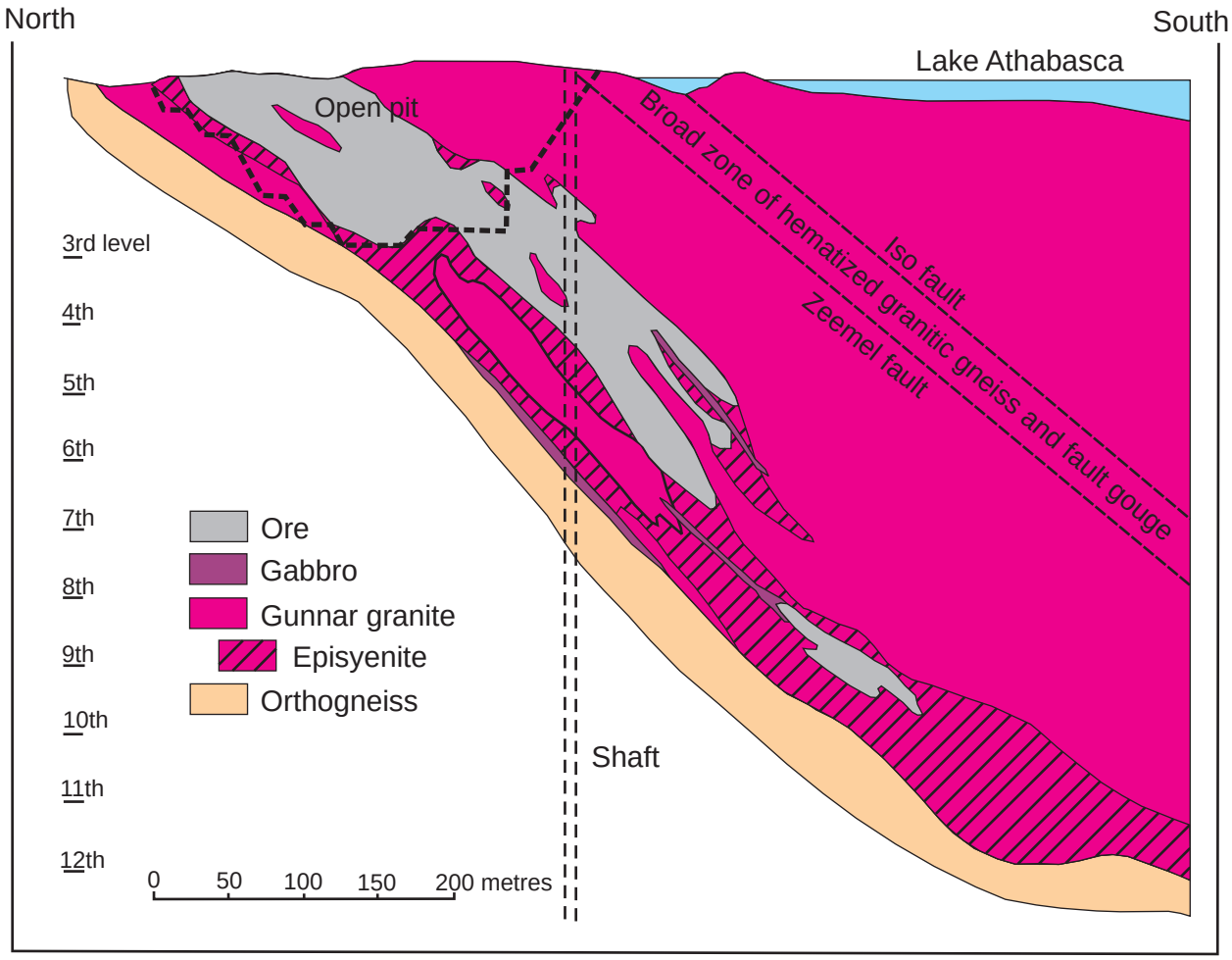


Figure 16 - Longitudinal cross section through the Gunnar orebody (after Evoy, 1986).

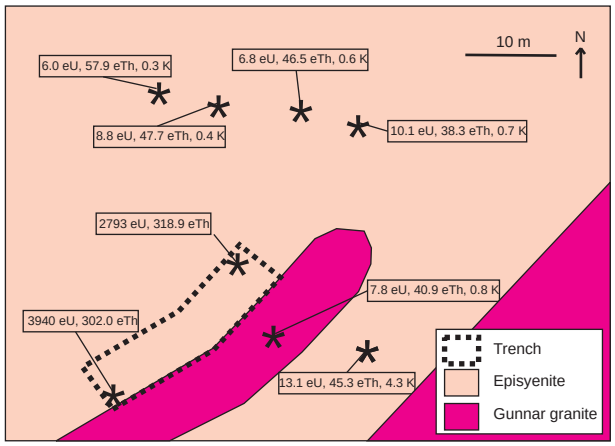


Figure 17 - Simplified geological map of the Spring Lake uranium locality (10KA123; UTM 618988 m E, 6585674 m N) showing spatial variation of eU in ppm, eTh in ppm, and eK in % relative to uranium showing (spurious % eK readings due to high U concentrations were not included).

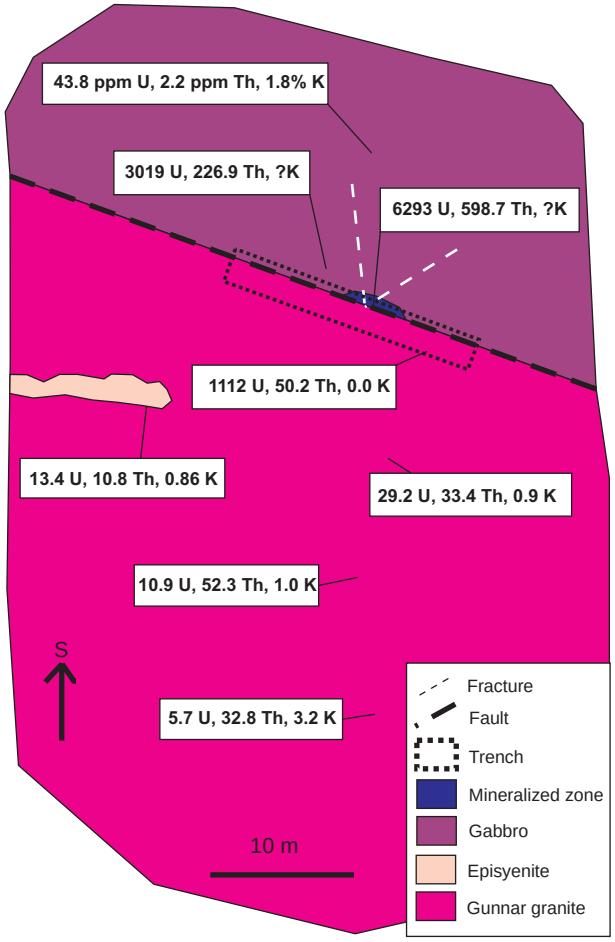


Figure 18 - Simplified geological map of uranium occurrence at the gabbro–Gunnar granite contact 1 km east of Gunnar pit (10KA235, Figure 3) showing spatial relationships of mineralization and alteration: eU and eTh values are in ppm, eK values are in %; ?K denotes spurious eK readings due to high U concentrations.

1) Within the episyenite zone, located 1 km northeast of the Gunnar mine, there are several uranium localities (Figure 3). At the westernmost locality (10KA235; UTM 621193 m E, 6585119 m N; Table 2), uranium occurs along a steep 110° fault contact between gabbro and Gunnar granite where it is intersected by steep 174° fractures (Figure 18). The Gunnar granite adjacent to the mineralized gabbro is bleached and highly fractured, but still contains ~25% quartz; however, one 1 by 10 m patch of episyenite recognized about 10 m into the granite contains 8% chlorite after biotite, 9% carbonate, 80 to 85% albite, and traces of leucoxene, hematite, and unidentified opaque and accessory minerals. Minor amounts of a second generation of albite are recognized in thin section by the absence of hematite inclusions. Uranium concentration decreases gradually from the main mineralization site, with anomalous values extending for at least 10 m into the gabbro and granite. The zone of potassium depletion extends about 20 m away from the mineralized fault, in both the minor episyenites and the quartz-bearing granites. The area between the episyenite and the mineralized fault is not exposed.

2) About 170 m farther east (10KA236; UTM 621353 m E, 6585057 m N; Figure 3), the Gunnar granite appears juxtaposed with granite of the orthogneiss unit along a thin (<1 m) discontinuous layer of chloritized and hematized amphibolite derived from the gabbro. The mafic layer is concordant to the 046° strike of S1 and is mineralized at the intersection of a steep 115° fracture. Spectrometer readings at the mineralized locality are: >10 000 ppm eU and 2941 eTh; eK readings were spurious and not useable (Table 2). Minor quartz-poor, hematitic quartzofeldspathic rocks may be episyenite.

3) About 550 m farther north near the western shore of Zeemel Creek is another uranium locality hosted by a ≥25 m thick medium-grained, massive to foliated (S1 strikes 060°) gabbro body (10KA179, UTM 621555 m E, 6585564 m N; Figure 3) devoid of any granitoid rocks at the outcrop scale. The mineralization is restricted to a single locale along a steep 155° fracture that has been trenched. Spectrometer readings were: 294.0 ppm eU, 15.2 ppm eTh, and 3.4% eK (Table 2).

4) About 1.5 km east of the Gunnar mine site (10KA084; UTM 621727 m E, 6584910 m N; SMDI #1207), a uranium locality is hosted by a gabbro sheet about 10 m thick within typical quartz-bearing Gunnar granite (Figure 3). Mineralization was localized at the intersection of steep 162° and 033° fractures in sheared and folded gabbro characterized by chloritization, hematization, and ribbed quartz veinlets. Spectrometer readings at the mineralized locality were 315.4 ppm eU, 10.8 ppm eTh, and 1.1% eK (Table 2), and 10.3 ppm eU, 32.0 ppm eTh, and 3.8% eK in the adjacent granite.

5) Approximately 1 km farther east lies another uranium locality hosted by a 10 m-thick gabbro sheet in Gunnar granite that is more mafic than usual, containing about 25% partially chloritized biotite (10KA090; UTM 622899 m E, 6584766 m N; SMDI #2089; Figure 3). Seventeen trenches have been blasted across the gabbro perpendicular to its 060° trend. The mineralization occurs along a steep 112° fracture at its intersection with a steep 315° fracture. Spectrometer readings of: 2381 ppm eU, 62.1 ppm eTh, and 0.6 % eK characterize the main uranium locality (Table 2), which is also characterized by yellow uranium alteration and white albite(?) veinlets.

6) At a locality about 1.5 km north of the Gunnar Pit (10KA186; SMDI #1694), an extensive outcrop area is made up of about 35% granite of the orthogneiss unit, 50% gabbro, and 15% intrusive pink leucogranite. All rock types exhibit high shear and cataclastic strain. Several trenches expose uranium mineralization along moderately to steeply northwest-dipping contacts between centimetre- to metre-scale gabbro bodies and leucogranite sheets up to several centimetres thick. At least some of these contacts represent faults characterized by minor brecciation and 1- to 2-cm thick quartz veins, which also occur in steep north-northwest–striking and curvilinear orientations. The highest recorded spectrometer assay yielded 1260 ppm eU, 35 ppm eTh, and 0% eK (Table 2).

c) Uranium in Orthogneiss

On an island situated between Mudford and Hilyard islands in St. Mary's Channel, 1 km southwest of the Gunnar pit (10KA160; UTM 619637 m E, 6583828 m N; Figure 3; SMDI #1208), uranium mineralization is hosted by orthogneiss. The mineralization lies along a steep north-northeast–dipping fracture at the intersection with a steep southeast-dipping, foliation–parallel fracture and yields spectrometer values of 459.2 ppm eU, and 2.2 ppm eTh (Table 2). A 5 m thick gabbro body situated about 10 m to the east is also transected by the steep north-northeast–dipping fracture but is not mineralized. Minor north-northeast–striking quartz veining is present nearby. The immediate mineralized area is hematized, chloritized, and contains chlorite-quartz veining, minor sulphides, and yellow uranium alteration.

7. Ore Genesis

a) Role of Episyenite

Deposits hosted by episyenites are complicated by debate over whether episyenitization and mineralization represent one or two distinct processes. Some workers think that episyenitization is a late magmatic/deuteric (Charoy and Pollard, 1989; Recio *et al.*, 1997; Costi *et al.*, 2002) process, whereas others invoke the infiltration, boiling, and condensation of meteoric waters (Turpin *et al.*, 1990), and think that its role in mineralization is mainly to structurally prepare the host rock. Mineralization is thought by some to occur later, most commonly as a result of crustal extension and dyke emplacement (Petersson *et al.*, 2001; Cuney and Kyser, 2008b). Others, however, believe episyenitization and mineralization are linked and occur well after crystallization of the host rocks (Cathelineau, 1986), but still in a setting of crustal extension and dyke emplacement (Leroy, 1978; González-Casado *et al.*, 1996).

At the Gunnar deposit, the maximum ages of both episyenitization and mineralization appear constrained by metamorphism. Temperature conditions associated with the 1.91 to 1.90 Ga (Ashton *et al.*, 2009b) lower amphibolite facies metamorphic event (Ashton and Hartlaub, 2008) would have exceeded the 250° to 450°C range for episyenitization. Had the alteration taken place before this time, it seems unlikely that the enhanced porosity required for subsequent uranium mineralization would have survived. This post-magmatic age inference is supported by the recent recognition of episyenite alteration at several localities in the main Beaverlodge uranium district. These include the 'Intermediate Zone', located about 30 km to the northeast (UTM 640481 m E, 6607185 m N, Figure 2; SMDI #1369), where uranium occurred within a sheared medium- to coarse-grained granitic host. Metre-scale zones situated only tens of metres from the open pit appear devoid of quartz and contain only 0.3% eK relative to the 3.2 to 4.0% eK (n=4) in the main host granite. Although this granite could be part of the same *ca.* 2.3 Ga suite as the Gunnar granite, the host rocks at other episyenite localities are thought to belong to the *ca.* 1.93 Ga (Hartlaub *et al.*, 2007) pink leucogranite suite. These include the '46 Zone', located 33 km to the northeast in the immediate footwall of the St. Louis fault (UTM 645600 m E, 6606800 m N, Figure 2), where a 2 to 5 m thick continuous unit of episyenite containing abundant carbonate and minor specular hematite (Figure 19) occurs structurally between a breccia derived from Murmac Bay group quartzite (together with the episyenite forming the 'cataclastic quartzite and pink leucogranite' unit of Tracey *et al.*, 2009), and mineralized amphibolite. The Dubyna Lake uranium deposit (UTM 647902 m E, 6608182 m N, Figure 2; SMDI #1324) is also hosted by pink leucogranite that has undergone carbonatization and hematization. No spectrometer values are available, but thin sections reveal that the rocks in the pit are devoid of K-feldspar, dominated by hematite-dusted plagioclase, and contain only about 3% quartz, reduced from 15 to 20% in the surrounding rocks. Zones of 'carbonate albitite' or 'sponge rock' composed of albite and dolomite and deficient in quartz have also been recorded from the 2327 ±17 Ma Athona (Persons, 1983) and 1994 ±37 Ma (Persons, 1983) Box granites, host rocks to orogenic gold



Figure 19 - Carbonate-rich episyenite from the '46 Zone' in the footwall of the St. Louis fault (approximately UTM 645600 m E, 6606800 m N).

mineralization 22 m northeast of the Gunnar deposit (Figure 2; Rees, 1992). Thus, episyenitization is probably common in the Beaverlodge uranium district, but has not been widely recognized because the finer grain size of most host granites renders the removal of quartz less noticeable than at Gunnar. The occurrence of episyenite alteration in a variety of rock types and ages, including some as young as 1.93 Ga, indicates that it is not a result of late magmatic or deuteric processes.

b) Timing of Episyenitization and Uranium Mineralization

Following the 1.91 to 1.90 Ga amphibolite-facies metamorphic event, the southern Rae Province was subjected to tectonic shortening related to both the Trans-Hudson Orogen to the east and terrane accretion to the west (Ashton *et al.*, 2009b). The resulting D4 deformation caused widespread brittle-ductile faulting, which could have provided the conduits necessary for fluid flow. Trans-tensional D4 displacements along the Black Bay fault and other structures, facilitated deposition of the Martin group redbeds (Ashton *et al.*, 2009b) and emplacement of associated Martin mafic volcanic and intrusive rocks *ca.* 1.82 Ga (Morelli *et al.*, 2009). The Martin group extends along the western shore of the Crackingstone Peninsula to within 4 km west of the Gunnar mine and may have been closer in the third dimension due to regional folding and faulting prior to erosion. It is also exposed at, or at least in close proximity to, many of the other uranium occurrences in the Beaverlodge uranium district (Lang *et al.*, 1962; Beck, 1969; Ashton and Hartlaub, 2008), leading some previous workers to speculate that the Martin group had a genetic role in mineralization (*e.g.*, Langford, 1975, 1978). Detritus for the Martin group was locally derived, so would have included an abundance of the granitoid and supracrustal rocks in the Uranium City region that presumably represent the original source of uranium for the deposits. Geochemical analysis of 73 clastic sedimentary samples from throughout the Martin stratigraphic section in the Beaverlodge area revealed an average uranium content of only 3.6 ppm (D. Quirt, pers. comm., 2010), approximately half that contained in unaltered Gunnar granite (average of 7.0 ppm eU based on 95 spectrometer readings; Table 1). Thus, the Martin group may have been the source of uranium for the Gunnar deposit, particularly if it was subjected to an efficient leaching process that left these relatively low uranium concentrations, but based on the measurable concentrations today, the basement rocks appear to have been more fertile. The altered Gunnar granite (*i.e.*, episyenite) shows no depletion in uranium relative to unaltered Gunnar granite (averaging 9.2 ppm versus 7.0 ppm eU, respectively; Table 1), and thus was probably not the source of uranium.

Regardless of whether the Martin group was the source of uranium, it may well have been a key to mineralization. Metamorphism accompanying the D4 event did not significantly affect the Martin group because it was being deposited at the surface; however, randomly oriented, post-D3 muscovite and chlorite in basement rocks throughout the region suggest that greenschist-facies conditions were at least locally attained at depth. Quartz dissolution associated with sodium metasomatism is thought to take place under 0.3 to 1.5 kbar pressure and 250° to 450°C temperature conditions, and to be triggered by sharp changes in temperature or salinity (Cathelineau, 1986). It has also been shown that silica solubility is significantly reduced in fluids that have undergone boiling followed by condensation, and can lead to quartz dissolution (Pécher *et al.*, 1985). Heat for such a process could have been supplied directly by the metamorphic event associated with D4 deformation. Alternatively, the Martin group could have provided both fluids and heat, the latter by diagenesis or, more efficiently, by volcanism, which could have created the sharp temperature rise needed to induce quartz dissolution. Thus, episyenitic alteration and uranium mineralization could well have formed between 1.9 and 1.8 Ga, during greenschist-facies metamorphism or as a result of meteoric and/or basinal fluids associated with the Martin group.

Granite-hosted, vein-type uranium deposits with associated episyenitic alteration are generally classified as 'granite-related' and distinct from 'unconformity-related' deposits (International Atomic Energy Agency, 2009). However, proximity of the Gunnar deposit to the exposed Athabasca Group unconformity (about 8 km to the south at its closest) and its somewhat isolated position relative to the main concentration of uranium deposits in the main Beaverlodge uranium district (Figure 2) leaves open the alternative possibility that it represents a basement-hosted, unconformity-related deposit exposed by erosion of the originally overlying Athabasca Group. Although an unconformity-related origin linked to the Athabasca Group cannot be ruled out, it seems unlikely for two reasons. First, given the estimated 9° slope at the northern margin of the basin (S. Bosman, pers. comm., 2010), the

unconformity would have been approximately 1300 m above the Gunnar deposit prior to erosion, which seems too far removed to be affected by unconformity-related processes. Second, preliminary work on dating uraninite from the Gunnar deposit suggests that mineralization took place at approximately 2.0 to 1.9 Ga (Dieng *et al.*, 2010). While more work needs to be done to obtain a precise age, this estimate suggests that mineralization pre-dated deposition of the Athabasca Group, let alone the mineralization associated with it.

Existing U-Pb estimates for the age of the dominant epigenetic uranium mineralizing event in the main Beaverlodge uranium district are also imprecise and include 1780 ±20 Ma (Koeppel, 1968) and *ca.* 1860 Ma (Dieng *et al.*, 2010). A fluid study of the region revealed three separate fluids events in the 1.84 to 1.7 Ga interval between amphibolite facies metamorphism and deposition of the Athabasca Group (Rees, 1992).

c) Fluid Conduits

In the immediate vicinity of the Gunnar deposit, the St. Mary's Channel, Zeemel, and Iso faults are all thought to have formed during D4 and exhibit convincing evidence of fluid transport (Figures 14 and 15). There is a spatial relationship between the episyenite and some of these and other faults suggesting a possibly genetic link (Figure 3). Further, subsequent extensional reactivation of D4 faults post-dated deposition of the Martin group (Ashton *et al.*, 2009b) and could have provided a link between Martin basinal fluids and the D4 fault network in the basement. Evoy (1986) suggested that the orthogneiss–Gunnar granite contact was more important than the D4 faults as a pathway for the fluids responsible for episyenitization at the Gunnar deposit. The orthogneiss is much more highly fractured, hematized, and epidotized within about 200 m of the Gunnar granite contact there (Figures 6 and 14), supporting the idea that this rheological boundary may well have served to focus brittle deformation and fluid flow. The episyenite itself provided the best immediate conduit for fluid flow at the mine site. It is probably no coincidence that the mineralized part of the episyenite is also brecciated (Evoy, 1986). Whether this is due to collapse of the highly porous episyenite or subsequent tectonic reactivation is unclear. At most of the localities other than the Gunnar deposit, uranium mineralization occurs along, or at the intersection of, open fractures. Although fractures in a variety of orientations were mineralized, steep northeast- and east-striking fractures were the most common, similar to findings in the main Beaverlodge uranium camp to the northeast (Tracey *et al.*, 2009). It is unclear whether the fractures were important fluid conduits during the main mineralizing event as inferred by Evoy (1986), or only during subsequent remobilization.

d) Precipitation of Uranium

Precipitation of uranium from an oxidizing fluid is most commonly attributed to a redox reaction. Small quantities of ferrous iron are available in sulphides within the host granites and gabbros as a possible reductant, but the absence of high concentrations in the immediate mine area suggest that precipitation may have resulted from an alternative mechanism. Solubility of uranium can be affected by a number of other parameters including changes in temperature, pressure, and pH (Romberger, 2006). Sharp temperature changes have already been cited as one means of bringing about quartz dissolution and could have been provided by Martin volcanism. Alternatively, the mineralogical changes brought about by episyenitization may have resulted in volume changes and/or a local drop in confining pressures if a network of voids within the episyenite remained open. Reactions associated with quartz dissolution and albitization may have resulted in other potential uranium precipitation mechanisms by changing the pH of the fluid.

8. Conclusions

The Gunnar mine exploited a granite-related uranium deposit hosted by the 2321 ±3 Ma Gunnar granite near its contact with Archean orthogneiss. Mineralization occurred in a brecciated part of the granite within episyenite, an alteration of the granite resulting from quartz dissolution and replacement of primary K-feldspar and plagioclase by albite. It is unclear whether the uranium was leached directly from the relatively fertile host rocks or was recycled through the unconformably overlying, *ca.* 1.82 Ga Martin group. The fluid or fluids responsible for episyenitization and mineralization may have been: 1) meteoric, 2) derived from a weak *ca.* 1.8 Ga metamorphic event, or 3) derived from the Martin group. Heat required to facilitate fluid circulation and quartz dissolution may have been generated during the metamorphic event or by mafic magmatism associated with Martin volcanism and widespread dyke emplacement at 1.82 Ga. Based on previous pitchblende ages and the recognition of episyenite alteration at several other uranium localities in the Beaverlodge camp, the Gunnar deposit is not thought to be a basement-hosted, Athabasca unconformity-related deposit.

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